MILLENIUM TOWER, SAN FRANCISCO
Settlement, Tilting and Repair
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• Constructed 2005-2009
• 58 stories, 645 ft (197m) tall
• Tallest & most expensive residential tower in San Francisco
• Views from the Sierra to the Cascades to the Farallon Islands
• Most expensive unit sold in 2013 for $13.5 million
• Construction Cost - $600 Million  Sales Cost - $750 Million
Some Homeowners

Joe Montana
Hall of Fame Quarterback

Hunter Pence
San Francisco Giants Superstar
The Site

- 350 Mission 2012
- Transbay terminal and track tube 2009-2017
- 301 Mission 2005-2009
- Salesforce Tower 2014-16
- 200 Beale 2017-18
History of the Problem

- **Groundbreaking – 2005**
  - Settlement predicted 4”-6”

- **Construction completed 2009**
  - Settlement reached 10”
  - Transbay Terminal excavation starts

- **Last unit sold in 2013**
  - Settlement 13”

- **SGH retained in 2014**
  - Settlement 15”

- **Litigation initiated in 2016**
  - Settlement 17”

- **Adjacent construction complete 2017**
  - Settlement 18”, Tilt 17” to northwest
Why did this happen?

San Francisco Downtown

Area of “infirm” soils based on SF General Plan
Subsurface conditions

10’ thick mat
75’ piles deep into Colma Sand

20’ (6m) – fill & rubble
loose sand, brick, concrete, gravel

30’ (10m) – Young Bay Clay
marine deposits – last 12,000 years

35’ (12m) – Colma Sand
cemented sands with clay binder
(bearing pressures up to 6 -8 ksf)

140’ (45m) – Old Bay Clay
overconsolidated clays with layers of silts and sands

Franciscan formation
Sandstone, Siltstone, Claystone
Serpentine
Other SF buildings with this foundation
The Millennium Tower

Superstructure
200,000 kips

Substructure
24,000 kips

Imposed bearing pressure
224,000 kips
100 x 200' bearing area
11.2 ksf
Why the settlement?

- Consolidation of Old Bay Clays
- Prolonged dewatering due to construction of adjacent projects exacerbated the situation
  - 2009-2014 – Transbay Terminal and Train Tube
  - 2013-2015 – 350 Mission Street
  - 2014-2016 – Sales Force Tower
- Adjacent construction completed
  - Water table rose
  - Effective stress on Old Bay Clays decreased
  - Old Bay Clays went into secondary compression (creep)
    - Left unchecked, over a period of 30 years, could double primary compression
How has settlement varied with time?

- Planar Average developed by fitting plane through data
- Contour plot illustrates July 2020 elevations [NAVD88, ft]
How has tilt varied with time?

(a) north-south

(b) east-west
Our assignment

• Determine if the settlement had significantly affected the building’s structural and seismic safety
  – Is it “safe”?

• Determine if retrofit is necessary or feasible
Structural System

- 58 stories
- 1 basement
- 10’ thick mat with 960 piles
- Post-tensioned flat slab floors
- Central core wall with outriggers
- Perimeter moment frames
Linear Analyses
Modeling

- **ETABs software**
  - Frame elements
    - Beams
    - Columns
  - Wall (panel) elements
    - Walls
    - Coupling beams
    - Outriggers
  - Shell elements
    - Foundation mat
  - Piles modeled as fixed translation points at shell nodes
Settlement Representation

- **Input 38 points into Surfer 8 software**
  - Provides smooth contours matching discrete points
- **Imposed enforced displacements on mat**
Effect of Settlement
Linear Results (Settlement)– Moment Frames

- DCRs under settlement are generally less than 30%
- Columns at base DCR~0.9
Linear Results (Settlement)
Shear Core and Outriggers

- Shear walls have low DCRs
- Outriggers, and outrigger columns have DCRs in range of 1 to 3
- No observable damage in these areas

Note: Values are ratios of shear stress to $\sqrt{\gamma}$.
Linear Analysis (Settlement) – Mat Foundation

- Flexural DCRs limited, but high shear DCRs along boundary of core
- Conclusion, linear analysis was not predicting the behavior well
- Use Nonlinear Analysis

Note: Values are out-of-plane shear and flexural DCRs

fDCR = Flexural DCR
vDCR = Shear DCR
Non-Linear Analyses
Nonlinear Analysis

- Perform 3D software
- Frames modeled using nonlinear 2D elements
- Walls and outriggers modeled using fiber elements
- Foundation
  - 2D grid frame nonlinear beam elements
  - Nonlinear springs (piles)
Mat
Nonlinear modeling
Outrigger coupling beams

Perform-3d Outrigger coupling beam, A/R = 0.5

Compared to A/R = 1.0 from a 2005 test by Canbolat et. al.
Pile Geotechnical vs Structural capacity

Maximum Geotechnical Compressive Capacity = 1175 kips

Pile Compressive Capacity @ Weakest section = 1227 kips
Nonlinear pile springs

Normalized Pile P-Z

Soil springs at vault

Mission Street

Fremont Street
Simulation of Settlement

1. Apply compression only springs to mat
2. Apply Gravity Loads
3. Impose negative thermal loading on piles to produce dished shape
4. Iterate to produce desired shape
5. Adjust spring tops flush with the mat and reattach
Gravity + Settlement Displacements
Mat Grillage Inelastic Rotations

Gravity

- DCR>0
- DCR>0.25
- DCR>0.50

Max = 0.4%
Pile Lateral Response

XTRA CT

LPile

SAP2000
Pushover Conditions
Pushover Analyses

Negative 1% rotation

Nil rotation

Positive 1% rotation
Pile Pushover Analyses

Mean displacement demand on piles
Ground Motions
Acceptance Evaluation

- Acceptance evaluation used PEER TBI - Tall Building Guidelines
  - Performance-based design procedure
  - Global performance
    - Residual and permanent drift
    - Unacceptable response limited
  - Element Performance
    - Response does not exceed valid range of modeling
    - Force-controlled elements provide acceptable margin against failure
Results
Building Tilt - Gravity + Settlement
Shear Wall Shear Drift

Shear wall shear gage drift - Average Results

All load cases include 1.00L + 0.25LL

UR: Shear wall shear gage drift - CP

Increment due to settlements (%)
Outrigger Coupling Beams
Column Plastic Rotation

![Graphs showing column rotation - average results.](image-url)
Mat Grillage Inelastic Rotations

Avg 7 GMs

- DCR > 0
- DCR > 0.25
- DCR > 0.50

Max = 0.4%

May 2017
Conclusions

- Building seismic response considering settlement is essentially the same as that neglecting it.
- Building essentially meets criteria for new buildings designed using performance-based procedures.
- The settlement has not substantially affected the building’s adequacy.
- Retrofit not required.
- Homeowners insisted on a substantive retrofit to “revalue” their units
  - Installation of 400+ piles to rock through the mat, jack load off the existing foundation.
Perimeter Pile Upgrade
Perimeter Pile Upgrade

Design Objectives

- Arrest Settlement
- Recover a portion of tilt
- Remove sufficient stress from the consolidating Old Bay Clays to:
  - Take the OBC layer out of primary compression
  - Upgrade the building’s seismic performance (secondary benefit)
- Demonstrate the building continues to meet applicable City of San Francisco requirements
[BS] 403.9 Voluntary seismic improvements. Alterations to existing structural elements or additions of new structural elements that are not otherwise required by this chapter and are initiated for the purpose of improving the performance of the seismic force-resisting system of an existing structure or the performance of seismic bracing or anchorage of existing non-structural elements shall be permitted, provided that an engineering analysis is submitted demonstrating the following:

1. The altered structure and the altered nonstructural elements are no less conforming to the provisions of the California Building Code with respect to earthquake design than they were prior to the alteration.
2. New structural elements are detailed as required for new construction.
3. New or relocated nonstructural elements are detailed and connected to existing or new structural elements as required for new construction.
4. The alterations do not create a structural irregularity as defined in ASCE 7 or make an existing structural irregularity more severe.
Design Concept

- Install 52 new piles to rock along north and west building edges
- Construct extension of 10’-thick mat
- Jack piles to remove 41,000 kips (18%) of the building weight
- Pile to Cap connection detailed to limit load transmitted to new piles under long term residual settlement
Settlement Analysis Overview

• Real problem is coupled visco (creep)-hydro-mechanical soil behavior with 3D soil-structure interaction
  – Difficult to calibrate
  – Time intensive to understand sensitivity
• Simplified uncoupled approach to problem
  – Perform an “elastic” FLAC3D analyses
  – Assess variability externally with logic tree analysis
• Effects from past/future construction activities not included
• Consolidation only in the OBC, and is double-drained
• No load transfer from PPU piles to soil
• Immediate settlement only considered for initial loading
• Groundwater surface is planar, but non-uniform across site
Settlement Analysis: Flowchart

FLAC3D “Elastic” Stress Analysis

Parallel 1D Column Settlement Analyses

Bayesian Inference via Logic Tree Approach

Final Settlement Estimates and Statistics
FLAC3D Analysis: Domain
1D Columns: Consolidation & Secondary

- Consolidation progression based on isochrones
- Effective stress calculated from remaining excess pore pressure and induced vertical building stress

Logic Tree Analysis: Overview

• Statistical analysis to determine mean and epistemic uncertainty of the consolidation parameters
• Parameter profiles with depth characterized by multilinear interpolation models
• Other variables considered:
  – Stress change in soil due to MT loading ($\Delta \sigma_v$)
  – Groundwater recharge level
  – Groundwater slope across MT footprint
  – Current (2019) percent consolidation
• Each settlement component calculated independently
  – Immediate settlement ($s_i$), Consolidation settlement ($s_c$), Secondary compression ($s_s$)
• Validated by comparing the mean value to the observed settlements in 2011
Logic Tree Analysis: Pre-Bayesian Updating
Logic Tree Analysis: Bayesian Updating

![Graphs and charts showing probability density and cumulative probability density distributions for the difference between best estimate and measured settlement in 2011.](image)

![Map showing distance along Mission Street with measured settlement data.](image)
Results: Stress Reduction and OCR
Results: Expected Median Additional Settlement
Results: Potential Additional Settlement
Retrofit Piles

36 inch through Colma sands

24 inch to Franciscan

20 inch in Franciscan
Foundation Upgrade Details
Project Schedule

- City-appointed peer review approved retrofit on 4 December 2018
- Parties settled dispute in October 2020
- Construction started Nov 1, 2020
- Indicator Pile installation now underway
- 22-month duration
- Monitoring of pile loads, settlement and piezometric head in soils for 10 years
Conclusions
& Summary
Conclusions

• Settlement has not impacted the building’s seismic resistance
• There is no reason, structurally that the building needs to be upgraded
• Homeowners needed a major retrofit to “revalue” their units
• Perimeter pile upgrade will have a cost of approximately $100 million
• Construction completion forecast for fall, 2022
Aftermath

- All new high rises in San Francisco “infirm soil” areas now use piles extending to rock
- City of San Francisco now requires geotechnical peer review of all high-rise buildings
- City has adopted an Administrative Bulletin governing the criteria for foundation review
Recent Work
Borings and Instrument Installation
Indicator Pile Installation
Indicator Pile Installation
Questions?